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Rapid Excavation and Mining (REAM) System - Revisited

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Rapid Excavation and Mining (REAM) System - Revisited

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Abstract

The rapid excavation and mining (REAM) system utilizes large- and medium-caliber smoothbore cannons to launch inert kinetic energy (KE) projectiles to spall rock fascias for mining and excavation applications. Historically, field tests have been conducted against various obstacles, and two test bores 3.5 m in diameter were excavated into granite, one of which was taken to a test depth of 17 m.

A cost analysis has been performed using the experimental data collected from the program in the 1970s. Advance rates that were limited only by the estimated ability to remove muck were assumed in this analysis. These assumptions lead to boring rates that were not only more than three times faster than conventional drill and blast (D&B) techniques but also considerably cheaper. The economic analysis has been recomputed with the aid of empirical cost functions from the U.S. Bureau of Mines (USBOM). It has been found that, under certain circumstances, the REAM technique uses less propellant per kilogram of ore produced than conventional D&B methods. Also, if cost is not an issue, then the REAM technique can provide advance rates unobtainable by conventional methods.

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1. Introduction

The rapid excavation and mining (REAM) device utilizes kinetic energy (KE) projectiles to spall rock fascias for mining and excavation. The method was introduced by Physics International (PI) (Watson 1972) during the early 1970s as a technique to rapidly construct tunnels for weapons and bunker installation under an Advanced Research Programs Agency (ARPA) contract (Olson 1975).

The proposed applications include (Watson 1972, 1973) rapid tunneling in hard rock, excavation, clearing of vertical shafts or stopes, augmentation of conventional drill and blast (D&B) methods for tunneling, remote breakage of large boulders for surface and subsurface mining, remote outcrop removal, avalanche control, and underground coal mining. Military applications include rapid defensive emplacement (foxholes), obstacle removal, and bunker neutralization. Safety is an important factor to consider with use of KE projectiles instead of explosives. Currently, the Russians (Arens, Zaidenbarg, and Smirnov 1997) are developing a recoilless cannon device for clearing blockages in vertical shafts as would be found in block caving. Remote operation of the REAM system provides safety during such operations and eliminates the need to use a pole to physically place a clearing charge in the blockage area. There is no chance for hang-fire or poor detonation timing to occur with KE rounds.

This technology was to be developed by John Watson of Gun Rock Inc., in the 1970s. However, following what appeared to be a successful demonstration, the REAM system and associated technology research and development ceased and was not pursued for more than 20 years.

REAM technology is currently being examined with the objective of re-establishing the associated technical and economic benefits. Also, we plan to examine enhancement of the REAM methodology through improved projectiles, propellant, and charge designs. Also to be addressed are concerns of muzzle blast and propellant product gas management. REAM technology is expected to be found attractive for a number of dual-use applications.

The Army's interest in this study is twofold. First, data from projectile impacts will support basic rock mechanics research with high-pressure/high-strain-rate constitutive information for hydrocode models. This information will be useful in modeling and breeching fortifications such as bunkers and other barriers. Second, the REAM system itself could assist the Army Corps of Engineers in rapid construction projects.

2. Physical Description

The REAM system consists of a smoothbore cannon firing inert KE projectiles to cause rock fascia spall or fracture of boulders. This spall/fracture is the result of strain energy dissipation through crack formation. The U.S. Army Research Laboratory (ARL) performs experimental and theoretical research in penetration and spall, as shown in Figures 1 and 2.

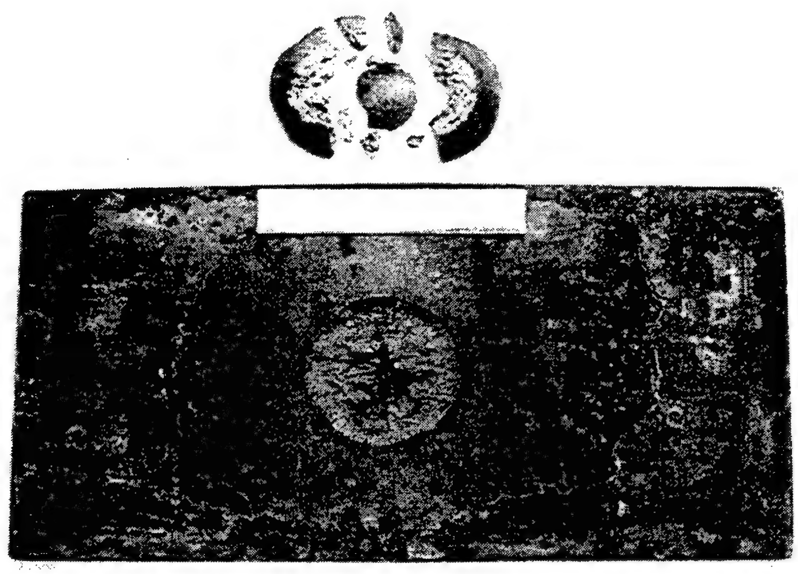

Figure 1. Spall of Armor Plate Caused by Blast-Induced Strain (Walters and Scheffler 1993).

Other items associated with the REAM system include muzzle devices for propellant gas collection and muzzle blast mitigation, as well as shielding to deflect spall and blast away from the equipment. Depending upon the application, remote operation may be necessary.

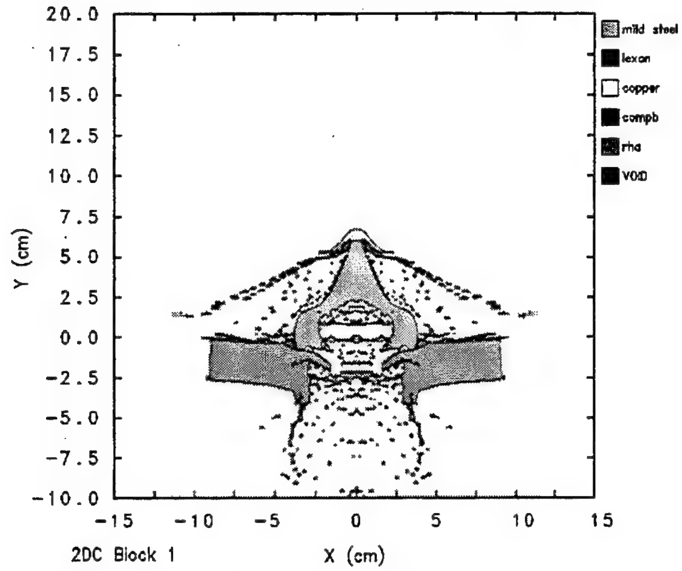

Figure 2. Numerical Simulation of Spall Caused by Blast-Induced Strain (Walters and Scheffler 1993).

3. Historical Results

The PI REAM project produced several experiments, using both 105-mm and 57-mm smoothbore cannons, all of which were successful or informative. Some of the experiments included destruction of obstacles such as boulders or precut granite blocks, as shown in Figures 3 and 4.

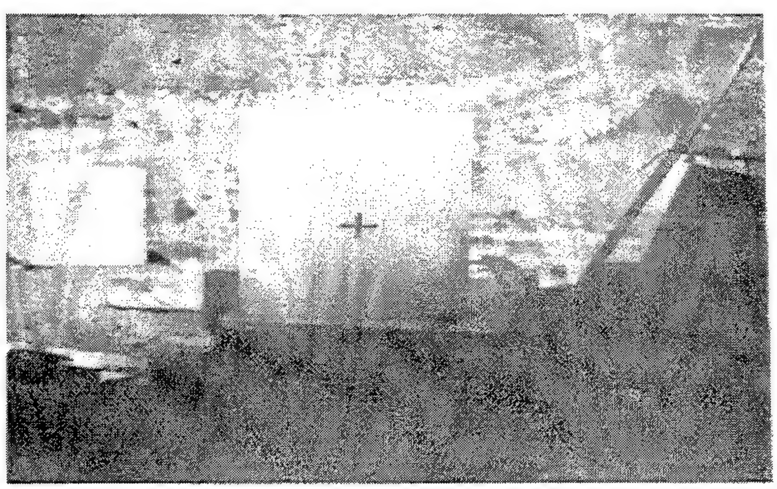

Figure 3. 1.2-m Granite Cube Before Inert Steel Projectile Impact (Physics International 1972).

Figure 4. 1.2-m Granite Cube After Inert Steel Projectile Impact (Physics International 1972).

Other experiments included two tunneling efforts (Watson 1972). The entrance circumference for both tunnels was prepared in a conventional manner with presplitting holes, the purpose of which was to dissipate or reflect the strain energy at the future tunnel wall near the mouth. After the tunnel was deeper, away from the mouth effects, these stabilizing presplitting holes were found to be unnecessary.

The first of the two attempts resulted in failure as the mouth region of the hole collapsed due to rock structure instability. Also, the face of the first hole was prepared using conventional D&B methods which, was thought to contribute to the instability.

Figure 5 shows the second tunnel in which the depth is 7.3 m and diameter is roughly 3.5 m. The original rock face in this case was prepared with the REAM gun system, which may have contributed to the success because of the relatively low-level energy transfer from the projectile to the rock face in comparison to D&B methods. A total of 205 rounds was required to produce the hole in Figure 5, resulting in an average of 28 rounds required to advance 1 m in depth. This second tunnel was bored to a final depth of 17 m, using both 105-mm and 57-mm smoothbore cannons. The 57-mm cannon was used to "trim" the walls and specific boulders identified for breakage.

Figure 5. Excavated 7.3-m-Deep Bore Hole (Physics International 1972).

During the advancement of the second hole, the average amount of rock broken per round was reported to be 1,360 kg (Olson 1975). Projectile impact during the excavation can be seen in Figure 6. Light from the muzzle blast of the cannon to the right of the photo illuminates the area, while light generated by the pyrophoric nature of the inert projectile illuminates the impact. The projectiles weighed 4.5 kg and were made of concrete reinforced with end plates of aluminum, with a plastic seal at the rear face (obturator) surrounded by a cardboard liner, as shown in Figure 7. The aluminum end plates prestressed the concrete to enable it to withstand the expansion at muzzle exit. Upon impact, the projectiles disintegrated, thus eliminating the possibility of ricochet. Propelling charges consisted of 10.9 kg of multiperforated propellant. This projectile/propellant combination in the 105-mm smoothbore cannon resulted in a muzzle velocity of 1,737 m/s or over 16 MJ of KE at the muzzle.

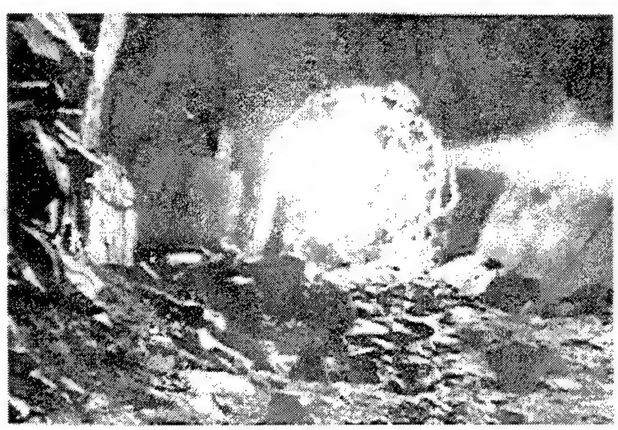

Figure 6. Projectile Impact on Rock Fascia (Physics International 1972).

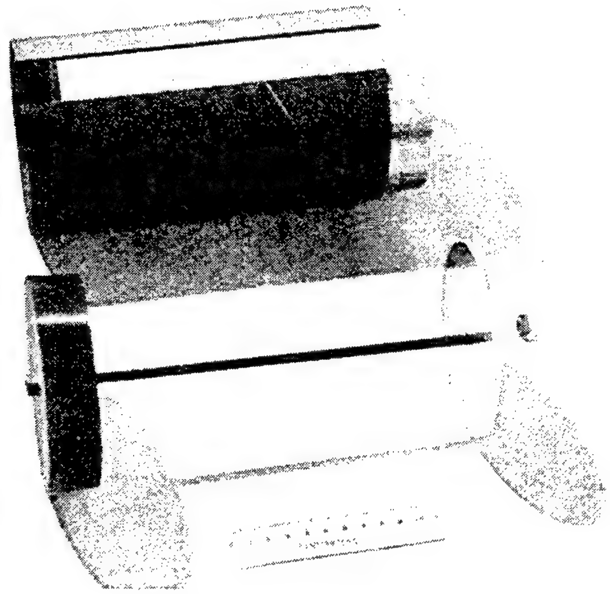

Figure 7. Final Concrete Projectile Assembly (Physics International 1972).

4. REAM-Specific Issues

During the investigation of the system, some issues/deficiencies were found in the following areas when applied in an underground situation, each of which is thought not to be insurmountable.

4.1 Noxious Gases. The exhaust and management of any combustion products and atmospheric control in an underground mine is a considerable task. This is an issue for any device that consumes hydrocarbon fuel. Specifically, for a REAM gun system similar to the original, the amount of product gases per round is equivalent to 13.3 m^3 of gas at standard atmospheric conditions. Firing at a rate of one round per minute, a future REAM system will have a gas management system at the muzzle to collect the combustion products. Such a system to route the gas rearward to an air pump and air handler for exhaust is in the concept stage. Diversion of product gases from muzzle flow will greatly reduce the muzzle blast. The air handler is to be incorporated into existing air management systems that maintain the air quality. The chosen or designed propellants would also assist in

minimizing the muzzle flash and secondary blast, as well as noxious products (Klingenberg and Heimerl 1992).

4.2 Audio Shock. Audio shock from the cannon was an issue with the REAM guns used in the 1970s, which did not incorporate gun gas control muzzle devices; thus, muzzle blast was severe. Future REAM gun systems would suppress muzzle blast by incorporating muzzle attenuating devices that would capture and divert most of the product gas. Through propellant formulation, the secondary muzzle blast and the NO_x products can be reduced and possibly eliminated (Klingenberg and Heimerl 1992). If further blast reduction is required, then a dampening baffle system for the mine head would also have to be incorporated.

4.3 Impact Shock. Tunneling and mining operations deal with varying rock formations, some of which are unstable. It should be recognized that REAM may not be suitable for all situations. Current tunneling processes may be most effective in cases of extremely unstable formations, as evidenced in the 1970s experiment when the first test bore tunnel mouth collapsed. Imparting 16 MJ of energy to a rock fascia is not inconsequential, as evidenced in Figure 8. However, 16 MJ is less than the energy pulse imparted to the mine head by conventional D&B methods (Langefors and Kihlström 1978). It was thought that the first experimental tunnel mouth collapsed due to the preparation of the rock fascia using conventional presplit D&B methodology. Also, neither rock bolting nor shotcreteing of the mouth area were performed during the experiment. It should be further noted that, in the second experimental tunnel, neither rock bolts nor shotcrete were applied, and this tunnel resulted in success. Possibly, rock strata defects were not recognized in the first tunnel, and this led to the unstable situation.

5. Cost Analysis

Historically, a cost analysis was performed on the data from the 1973 experiment by Jacobs Associates of San Francisco, CA (Olson 1975). The results of that analysis, as well as a more up-to-date analysis, are presented.

Figure 8. Blast From Impact With Small Ejecta (Physics International 1972).

5.1 Original Cost Analysis. Table 1 provides tunneling rate information based upon the 1973 experiment. The tunneling rate appears large, but the firing rate of one shot per minute is modest considering current cannon firing rates. The daily theoretical advance assumes that adequate muck removal equipment is in place.

Table 1. Theoretical Tunnel Advance Using a 105-mm Cannon (Olson 1975)

No. of Cannons	No. of Rounds Per Hour	Theoretical Advance	
		3-m-Diameter Tunnel (m/day)	6-m-Diameter Tunnel (m/day)
1	60	62	16
2	120	124	33
3	180	186	52
4	240	249	69

The historical cost analysis is presented for hard rock tunneling examples of both 3-m and 6-m-diameter tunnels in Table 2. It must be noted that this original cost analysis was performed for a tunneling exercise and not a mining scenario. The results of the original study show a large savings in labor. According to the 1973 Jacob Associates analysis (Olson 1975), estimated theoretical REAM tunneling costs were 30–40% less than the D&B technique.

Table 2. Original Estimated Cost Comparisons for REAM vs. Conventional D&B After Olson (1975). Costs Are Per Linear Meter Adjusted for Inflation (1998$/1974$ = 3.3) (U.S. Consumer Price Index 1998).

Item	3-m Tunnel		6-m Tunnel	
	REAM at 69 m/day ($/m)	D&B at 20 m/day ($/m)	REAM at 168 m/day ($/m)	D&B at 21 m/day ($/m)
Labor	42.00	96.00	37.00	158.00
Materials and Supplies	21.95	14.70	42.20	40.00
Equipment Operation	5.60	16.50	9.10	33.00
Overhead	9.75	24.20	14.50	30.00
Plant	21.80	20.00	32.00	28.00
Equipment Writeoff	28.05	24.00	50.00	42.00
Subtotal	129.15	195.40	184.80	331.00
Markup 17%	21.95	33.20	31.40	39.00
Total	151.10	228.60	216.20	370.00

Olson (1975) used an estimated advance rate of 69 m/day (16 hr) in a 3-m-diameter tunnel (see Table 2) which produced 1,450 short tons (st) of muck per day for a rock density of 2.7 metric tons (mt)/m^3. The analysis performed for PI and presented in Table 2 shows an advance rate for the REAM technique in a 6-m tunnel of 168 m/day. This rate appears large. Both REAM rates of 69 m/day and 168 m/day in Table 2 were selected by PI, based on the maximum amount of muck removal envisioned by PI. In addition, the labor costs are smaller in the 6-m case than in the 3-m case. This created some doubt of this analysis and, therefore, the second cost analysis of section 5.2 was performed.

5.2 U.S. Bureau of Mines (USBOM) Cost Analysis. The historical experimental results provide sufficient information to perform a simple independent cost analysis. The USBOM has created cost-estimating guides and tools using historical mining data and has incorporated these into a cost estimation package called PREVAL (Smith 1992). They also provide the functional forms of the estimations used in PREVAL (Camm 1991).

Although the previous analysis is for tunneling and the following correlations are for mining, an appropriate application may be made if the mine is designated a seam with dimensions and characteristics similar to that of a tunnel.

USBOM-specific cost models include the following in functional format using the mine depth, as well as the number of short tons mined per day (stpd):

(1) $\text{Labor} = 158(\text{stpd})^{-0.295} + \dfrac{2010}{\text{stpd}}$,

(2) $\text{Equipment} = 44.7(\text{stpd})^{-0.499} + \dfrac{0.325(\text{depth})}{\text{stpd}}$,

(3) $\text{Lumber/Steel} = 2.81(\text{stpd})^{-0.037} + 57.8(\text{stpd})^{-0.474} + 0.00014(\text{depth})$,

(4) $\text{Fuel/Lube} = 20.3(\text{stpd})^{-0.604} + 9.33(\text{stpd})^{-0.539} + \dfrac{0.090(\text{depth})}{\text{stpd}}$,

(5) $\text{Explosives} = 4.72(\text{stpd})^{-0.136}$,

(6) $\text{Tires} = 1.16(\text{stpd})^{-0.269}$,

(7) $\text{Const. Material} = 9.87(\text{stpd})^{-0.151} + \dfrac{200}{\text{stpd}}$,

(8) $\text{Electricity} = 94.6(\text{stpd})^{-0.483} + 0.0014(\text{depth})$, and

(9) $\text{Sales Tax} = 3.38(\text{stpd})^{-0.230} + \dfrac{133}{\text{stpd}} + \dfrac{0.025(\text{depth})}{\text{stpd}} + 0.00009(\text{depth})$.

These functions produce the cost per short ton for the mining operations. These functional fits may be applied to supply a detailed cost estimate of a REAM tunnel by using the historical data and other typical mine data provided in Table 3. The mine was assumed to be a seam of gold 3 m in diameter at a depth of 610 m, with a reserve of 1M st of ore with a grade of 1 tr oz/st.

Table 3. Nominal Parameters Involved in PREVAL Example

Mine Parameters	PREVAL Input/Output
In-Situ Ore Reserve	1,000,000 st
Mining Method	Cut and Fill
Mining Days/Year	260
Depth	610 m
Ore Grade	1 tr oz Au/st
Development Years	3
Ore Recovery	85%
Processing Method	Float Plant - 350 days/yr
Process Recovery	Au 76.00% at $350/tr oz

These fixed parameters for the mine were also used in PREVAL to produce the optimal mining and mineral processing rate as shown in Table 4. The REAM augmented advance rate of 69 m/day in Table 4 was the most conservative from the historical data in Table 2 using only one 105-mm smoothbore cannon, although this 69 m/day rate appears to be based on 100% utilization of mine equipment without accounting for downtime for maintenance or repair. According to Richard Robbins (Robbins 2000), utilization rates of between 30% and 60% are more typical. Bearing this probable 100% utilization rate in mind, the 69 m/day rate was used in the analysis.

Table 4. Nominal and REAM Mine Differences

Mine Parameters	Nominal	REAM
Advance Rate (m/day)	30.2	69.0
Mining Rate - Ore (st/day)	572	1,450
Mining Rate - Waste (st/day)	6	14
Mine Life (yr)	6	3
Processing Rate (st/day)	425	1,077

A cost analysis using the USBOM functions may be made using the PREVAL result of 572 st/day and a potential REAM tunneling rate of 1,450 st/day. These costs per short ton are

summarized in Table 5, assuming that the cost of explosives used in conventional methods is the same as the cost of propellants in the REAM method, which is not the case, as shown later. The resulting labor rate for REAM assumes the rate of the traditional D&B methodology.

Table 5. Computed Mine Cost Components From the Correlations of Camm (1991)

Cost Component	Nominal ($/st)	REAM ($/st)
Tunneling Rate	572 st/day	1,450 st/day
Labor	27.79	19.84
Equipment	3.02	1.63
Steel	3.13	2.11
Lumber	2.22	2.15
Fuel/Lube/Tires	1.27	0.72
Explosives	1.99	1.75[a]
Construction Materials	4.13	3.43
Electricity	7.21	5.61
Sales Tax	1.28	0.94
Total	52.05	38.18

[a] Economies of scale are accounted for.

A savings of over 25%/st is apparently realized with the 1,450-st/day rate due to economies of scale. If the limiting factor in the production rate is the drilling and blasting at the mine face, then incorporating the REAM system can increase this rate, making it possible to realize these economies of scale for items other than the propellants.

One further important item to realize is that the amount of explosives required per cubic meter for nominal methods and the amount of propellant required for the REAM system are not the same. Specific loading densities for parallel drilled rock fascias, as in the previous example, are about 3 kg of explosives per cubic meter (Langefors and Kihlström 1978). Using the explosives data from Table 5, this corresponds to $5.93/m^3 of muck, assuming a rock density of 2.7 mt/m^3. Each round from the 105-mm cannon in the REAM experiment used 10.9 kg to produce 1,360-kg muck. Thus,

the REAM-specific propellant density is 22 kg of propellant per cubic meter of ore. This implies that the REAM system uses about seven times as much energetic material per cubic meter of muck than conventional D&B methods. Table 6 highlights the comparisons between conventional D&B methods using the correlation values as well as Langefors data and REAM using the historic experimental data as well as propellant cost estimates. Using the aforementioned analysis, the price of the propellant for the REAM system, to be equivalent (kilograms of ore/kilograms of ore) to the mining system, should be \$0.27/kg, which is less than the current price of ammonium nitrate (AN) anfo grade, at \$435/mt or \$0.435/kg (AllChem 1998). This value, and Table 6, highlights the propellant economic issue. The possibility of developing a cheap propellant on the order of \$0.25/kg is not likely or realistic. One of the cheapest propellants manufactured for large-caliber cannon is on the order of \$15/kg. However, mining/tunneling profitability must be concerned with the total rate of return on investment, and a more sophisticated or comprehensive economic analysis may prove REAM to be more economically viable than shown.

Considering the issue of propellant cost, one example of a possible propellant source is the inventory of older military propellants. Currently, there are over 45M kg of propellants in the U.S. military reserves in the demilitarization process, with 23M kg of propellants added annually (Morris 1998). This propellant includes all charges for all calibers and weapon systems, and not all would be suitable for REAM applications. Analysis would show which propellants would be suitable or could be made so.

If cost is not the issue, as may occur in certain mining or tunneling scenarios where rate is of the utmost importance, then the REAM system would be beneficial. The increase in the mining rate that REAM provides is not necessarily possible with conventional D&B methods. If more REAM cannons were applied to the mine head, the REAM advance rate would further increase. This assumes the entire mine/tunnel infrastructure to grow in capacity to accommodate the increased REAM advance rate.

Table 6. Nominal D&B and REAM Cost Differences

Parallel Drilled Fascia	D&B	REAM (Propellant)
Explosive or Propellant kg/mt of Muck	$1.11 kg/mt	8.15 kg/mt
Explosive, Propellant Cost/mt Muck	$2.19/mt	~$122/mt
Explosive, Propellant Cost/kg	$1.97/kg	~$15/kg

5.3 D&B Comparison. The previous example may be thought to entirely dismiss the application of REAM to mining; however, there may be other more specific applications in which REAM may economically augment and assist conventional methods. One of these areas is in tunnel blasting with parallel hole cuts. Using tunneling data compiled by Langefors and Kihlström (1978), typical specific charge loading densities in D&B methods are about 3 kg/m^3 over the entire tunnel fascia. However, to open a center working hole requires a much higher loading density of explosives, as is illustrated in Figure 9. Specifically, one example is a Grönlund-type drill pattern using a hole spacing of 0.095 m between centers and a specific dynamite charge of 0.78 kg/m/hole in ore and granite (as shown in Figure 8). This cut results in a series of nine 30-mm holes in a square pattern. The specific dynamite charge in this region is 194 kg/m^3, or almost nine times the REAM-specific charge. Dynamite, which is no longer extensively used, costs between $2.20 and $13.20/kg (Ronay 1999). Under these conditions, the explosive costs are roughly the same per kilogram as propellants. Therefore, the REAM system may well be advantageous for clearing center working holes for tunnel or stope initiation. Thus, the REAM system, working in conjunction with conventional drill and blast methods creating a hybrid tunneling mechanism, would augment the advance rate.

6. Areas of Research

Areas of research include determining suitability of excess military propellants and newer formulations and designs for REAM-specific propellants, projectiles, impact physics, as well as

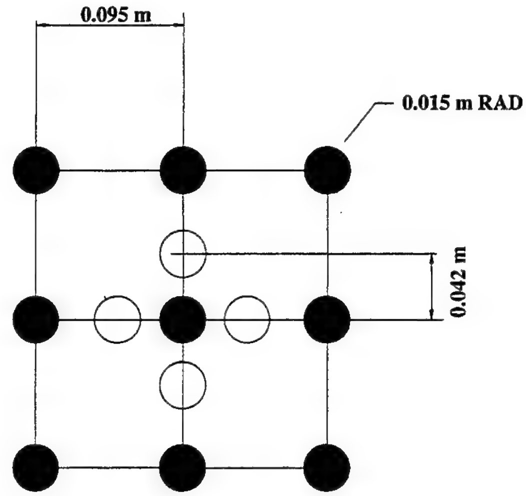

Figure 9. Grönlund-Type Burn Cut Example Using Four Vacant Holes to Blast Into With an Aspect Ratio of One (Langefors and Kihlström 1978).

muzzle devices for gas collection and blast suppression and REAM system integration. There have been great advances in ballistics over the past 25 yr since the PI study. In each of the PI research areas, no optimization or intensive design took place. Research in propellant designs will enable a relatively cheap propellant to be applied to the system. Propelling charge designs can be optimized such that the muzzle blast and flash are minimized, while providing the desired muzzle velocity. The projectile design of the 1970s was basic, while projectile-strata impact design and control is of the utmost importance in the performance of the entire system. Several types of KE projectiles should be considered to perform different tasks, one being a penetrator that causes radial fracture at depth. This type of projectile will produce a reflective boundary condition for subsequent rounds designed to maximize the fascia breakage or spallation.

Muzzle blast suppression devices and gas collection devices were previously referenced in section 4. These are extremely important to enable the use of such a device underground in confined quarters. Integration of the design with blast shields for ejecta, baffles for blast mitigation, and power for mobility, all incorporated with a conventional muck-gathering conveyer system, are other areas of research and development.

7. Discussion and Conclusions

The REAM methodology is envisioned to work alone or in conjunction with either conventional drill and blast methods or mechanical excavation devices, such as tunnel boring machines (TBM). The system will have cannon calibers, projectiles, and charges designed for specific geological or operational characteristics.

Although not discussed, the REAM device is inherently safer for dangerous operations, such as clearing stopes and chutes for block caving, than manually placing charges due to its remote operation. Also, avalanche control or remote outcrop removal without the hazard of duds is potentially useful.

REAM, as analyzed within this report, is not cost-effective when compared to conventional drill and blast methods for the entire fascia of parallel cut tunnels. The propellant costs are too prohibitive.

If the REAM system is applied to the center cut region of a parallel cut tunnel, then the system is cost-effective. Using the REAM system to start parallel burn cuts may increase hard rock tunneling advance rates and enable new levels of efficiencies which would be otherwise unobtainable.

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13. ABSTRACT *(Maximum 200 words)*

The rapid excavation and mining (REAM) system utilizes large- and medium-caliber smoothbore cannons to launch inert kinetic energy (KE) projectiles to spall rock fascias for mining and excavation applications. Historically, field tests have been conducted against various obstacles, and two test bores 3.5 m in diameter were excavated into granite, one of which was taken to a test depth of 17 m.

A cost analysis has been performed using the experimental data collected from the program in the 1970s. Advance rates that were limited only by the estimated ability to remove muck were assumed in this analysis. These assumptions lead to boring rates that were not only more than three times faster than conventional drill and blast (D&B) techniques but also considerably cheaper. The economic analysis has been recomputed with the aid of empirical cost functions from the U.S. Bureau of Mines (USBOM). It has been found that, under certain circumstances, the REAM technique uses less propellant per kilogram of ore produced than conventional D&B methods. Also, if cost is not an issue, then the REAM technique can provide advance rates unobtainable by conventional methods.

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